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PEREGRINE: Bringing Monte Carlo Based Treatment Planning Calculations to Today's Clinic

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Introduction

Monte Carlo simulation of radiotherapy is now available for routine clinical use. It brings improved accuracy of dose calculations for treatments where important physics comes into play, and provides a robust, general tool for planning where empirical solutions have not been implemented. Through the use of Monte Carlo, new information, including the effects of the composition of materials in the patient, the effects of electron transport, and the details of the distribution of energy deposition, can be applied to the field.

PEREGRINE™ is a Monte Carlo dose calculation solution that was designed and built specifically for the purpose of providing a practical, affordable Monte Carlo capability to the clinic. The system solution (see Figure 1) was crafted to facilitate insertion of this powerful tool into day-to-day treatment planning, while being extensible to accommodate improvements in techniques, computers, and interfaces.

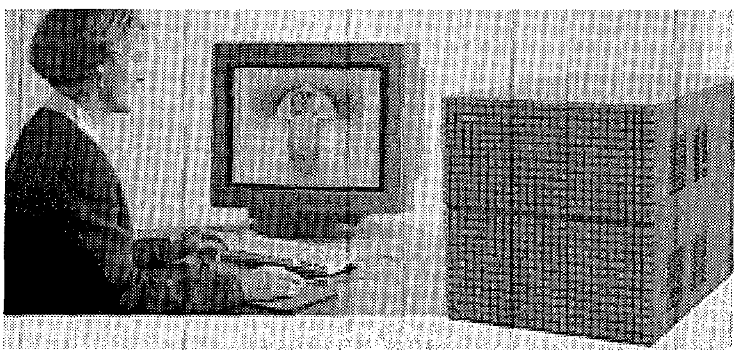

Figure 1: PEREGRINE dose calculation system.

History

Although the idea of solving equations through stochastic simulation was known for some time by statisticians, its power for solving complex, real-world problems was first recognized by von Neumann and Ulam in 1949. The advantage of the Monte Carlo method is that it allows one to arrive at an exact solution for a wide variety of problems that are too complex to be solved analytically.

Monte Carlo radiation transport has served an important role at Lawrence Livermore Laboratory since its founding in 1952. In the 1950's, transport was based on von Neumann's work, constrained to neutrons, and limited by knowledge of physical cross sections. Computations were performed on the ENIAC computer. Throughout the intervening years, LLNL physicists using increasingly powerful IBM, CDC, and Cray computers improved the physics representations and broadened the included particles, developed efficient algorithms, and implemented a plethora of special and general-purpose codes. In addition, LLNL physicists developed all-particle (photon, neutron, electron, and other charged particle) databases, many of which serve as the world standard today. In the early 1990s, the neutron and proton cross sections were extended to 250 MeV, driven by a growing number of requests from the medical community.

Each decade, efforts were made to apply Monte Carlo calculations to radiation therapy. However, until the 1990's, computers were too slow and expensive to support day-to-day use of Monte Carlo calculations to predict dose delivered to patients.

Several Monte Carlo codes have been used in the medical physics community for years for research, verification of dose calculation algorithms, shielding calculations, and limited clinical treatment planning. The most prominent general purpose Monte Carlo implementations used include EGS[1] and MCNP[2] (and codes based on them). Other Monte Carlo based approaches (such as those that use Monte Carlo to precalculate kernels and voxel Monte Carlo) have also been used in order to gain speed by incorporating simplifying assumptions.

The PEREGRINE program was undertaken to provide a system solution that makes Monte Carlo transport practical for day-to-day treatment planning. In order to accomplish this, we utilized the knowledge base gained in over 45 years of Monte Carlo development to design a new, single-purpose code for use in treatment planning for radiotherapy. Our purpose was to make Monte Carlo fast, inexpensive, and, most importantly, simple enough to be used by medical physicists, dosimetrists, and physicians in a working clinical environment. By creating a new system, we were able to include all the relevant physics (but only the relevant physics), utilize only geometries relevant to the clinical setting, create simple interfaces to existing treatment planning systems, and implement an application which very efficiently utilizes modern multi-cpu computer architectures and commodity hardware.

Physics and verification testing

PEREGRINE[3,4] simulates radiation therapy starting with a set of representative particles randomly sampled from distributions determined from offline simulations of the treatment-independent portion of the radiation source[4,5,6]. It tracks each photon, electron, and positron through the treatment-dependent beam delivery system and then through the patient using standard full-physics Monte Carlo transport methods. Treatment-specific beam modifiers such as collimators, apertures, blocks, multileaf collimators and wedges are modeled explicitly during each PEREGRINE calculation. The patient is described as a Cartesian map of material composition and density determined from the patient's CT scan.

PEREGRINE is designed to be accurate and fast. The accuracy derives from the high-fidelity cross-sections and proven transport methods used in modeling the particle transport and in the accuracy of the CT scan description of the patient. Speed is attained by numerous design techniques including:

- modeling the patient-independent radiation source offline
- the use of delta scattering in photon tracking
- the use of electron range rejection
- support for user specification of the resolution and extent of the dose reporting region

An extensive, measurement-based validation and verification process was undertaken to ensure the accuracy of PEREGRINE[7]. The simplest and most direct radiation source tests are open fields incident on water phantoms: depth dose for small to large fields, field flatness or horns for large fields, and relative output for small, large, and high aspect-ratio (rectangular) fields. In addition, depth dose comparisons for independent-jaw fields tests the adequacy of off-axis photon energy distributions.

Accurate photon particle-interaction data and transport algorithms are critical for determining relative attenuation and scatter in accelerator-head components, beam modifiers, and the patient. Their accuracy has been demonstrated by experimentally verifying the water-phantom dose distributions resulting from beam modifiers such as blocks, block trays, wedges, multileaf collimators, and compensators, in phantoms with step (discontinuous) and partial-cylinder (continuously changing) surface irregularities, and in phantoms with internal heterogeneities with high- and low-atomic number and high- and low-densities.

Accurate electron and positron transport is most important in regions of electron disequilibrium. These regions are located less than one electron range from a significant material boundary, such as the outer surface of the phantom or internal-heterogeneity surfaces. The dose predicted in the dose-buildup region near the initial patient or phantom surface depends on accurate electron transport for two reasons. First, dose is contributed directly by contaminant electrons produced in the beam delivery system and the air. Second, dose is contributed from electrons created by photon interactions in the patient or phantom (this is also an electronic disequilibrium area).

Finally, electron scatter into the monitor chamber may contribute to uncertainty in relative dose predictions. PEREGRINE™ uses published collimator jaw-dependent backscatter measurements[8] to estimate this correction to the absolute output per monitor unit. The accuracy of this approach is assessed in the beam delivery system tests.

Software architecture and implementation

The PEREGRINE system software design process was based upon a traditional top-down, process-driven, structured design methodology intended to reduce software complexity, enhance software reliability, and promote efficient software maintenance.

The software is organized into three specialized library component packages (see Figure 2). The PEREGRINE Monte Carlo library provides the single simple interface which all dose calculation executives utilize to perform each phase of the dose calculation: setup, particle transport, and finalization. This central library is designed to take advantage of both shared memory and message-based distributed computing environments and depends upon two supporting libraries that each focus on input/output (I/O). The Teletherapy Source Library (TSL) provides the interface for I/O of patient-independent beam delivery characterization data. The Treatment Planning Interface (TPI) provides the interface for I/O of patient-specific treatment planning data.

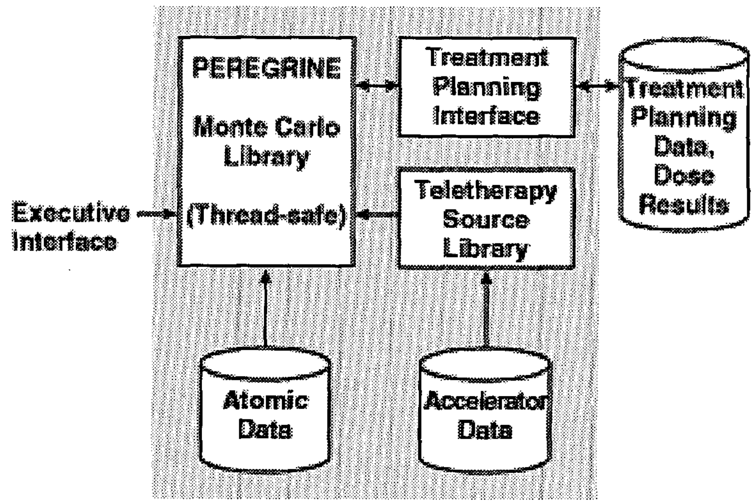

Figure 2: PEREGRINE software architecture.

In addition to the library interfaces, a common executive interface is defined to control access to critical shared resources which provides for increased flexibility during software development and testing. A simple single-threaded executive is utilized as a primary test-jacket to develop, debug, and test library code. The PEREGRINE product system is based upon a high-performance, two-tiered, distributed master/slave architecture designed to exploit computational resources in a scalable manner. The master focuses on the I/O bound phases of the dose calculation (setup and finish) and controls and coordinates multiple slaves. Master and slaves communicate using messages over standard networking protocols, including TCP/IP and UDP. Each slave focuses on the compute bound particle transport phase of processing and is designed to take performance advantage of multiple CPUs using shared memory and POSIX threads.

Hardware realization (PEREGRINE engine)

PEREGRINE is implemented with a master-slave, distributed architecture that runs on commodity, multi-processor x86 mainboards interconnected on a private network.

Each board runs the Solaris (Sun TM) operating system — the master board boots from a local disk, slaves are booted diskless by the master. The hardware components are assembled in a chassis module that contains power supplies, a hard disk, up to 6 mainboards, a small 100MB ethernet hub, and floppy drives (used to boot slave boards). Each mainboard supplies controllers for all peripherals used for operation on the private network; a single network card is required to access a public network. Mainboards are currently available with 733MHz, dual Pentium III (Intel™) cpus; the chassis will accommodate future board designs with faster processors and additional cpus. A typical 24 processor configuration uses two modules interconnected by a single network cable; additional modules can be added by a connection through an ethernet switch.

A PEREGRINE engine is attached to a treatment planning system via a conventional office network; dose calculation jobs are scheduled through a networked file system and a runtime fifo (first-in-first-out) queue.

The master executive is a tcl (tool-command-language) interpreter extended with routines from the PEREGRINE libraries and additional routines for threading and network distribution. A slave executive is a custom interpreter that incorporates and threads the key Monte Carlo transport routine. In operation, a master script implements a state machine that processes jobs submitted on the job queue. The master sequences a case through the routines of the PEREGRINE api for input and setup, distributes the job to all slaves (including slaves running on the master main board), collects and aggregates computed dose, and writes out result files. While a case is in progress, real-time statistics and dose views are available through an rpc (remote procedure call) interface for view on the host treatment planning system.

The PEREGRINE engine design achieves the following goals:

- simple setup
- expandable number of processors
- low life-cycle costs
- adaptable to new technologies

Conclusions

The PEREGRINE system has achieved the goal of providing practical Monte Carlo for use in clinical radiotherapy practice. A dose calculation engine has been designed, implemented, tested, and verified[3-7,9]. The technology has been licensed to NOMOS Corporation of Sewickly, PA, USA, and routine implementation in clinics is imminent. The challenges at hand include discovery of the specific uses which deliver the full potential of Monte Carlo, and furtherance of Monte Carlo in radiotherapy applications through improved measurement programs and the continued development of clinical solutions.

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